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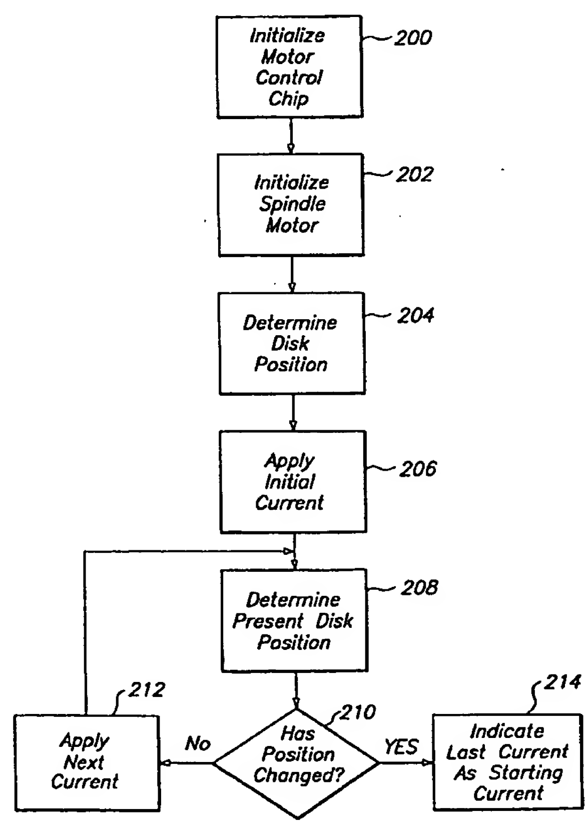
(54) Title: METHOD AND APPARATUS FOR IN–DRIVE MONITORING OF STICTION BY MEASUREMENT OF DISK SPINDLE MOTOR STARTING CURRENT

(57) Abstract

A method for in–drive monitoring of stiction in a hard disk drive and corresponding improved hard disk drive are provided. Stiction is monitored by measuring starting current of the spindle motor of the drive without having to remove the printed circuit board of the disk drive, open the disk drive, or remove the drive from a given test environment. The method includes steps of initializing the motor driver control chip (step 200), initializing the motor (step 202), determining an initial disk position (step 204), applying an initial current (step 206) and determining if the disk position has changed (step 208 and 210). If the disk position has not changed, then the method applies a next higher current (step 212) to the spindle motor, wherein the method repeatedly increases the current until the disk position changes (step 208, 210 and 212). The last applied current which caused the disk position to change becomes the starting current (step 208, 210, 212 and 214). The method is implemented as an on–board electronic torque meter (ETM) by integrating specialized firmware with the motor driver control chip, to produce an improved hard disk drive.



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METHOD AND APPARATUS FOR IN-DRIVE MONITORING OF STICTION BY MEASUREMENT OF DISK SPINDLE MOTOR STARTING CURRENT

Field of the Invention

The present invention relates to monitoring stiction in a hard disk drive system. More particularly, the present invention relates to a method and apparatus for in-drive measurement of the disk drive starting current in a non-invasive manner.

Background

Accurate and reliable measurement of stiction in a hard disk drive system is an important goal in drive development, as this measurement can be used for head and media qualification, failure analysis of a drive, or even advance warning of rising stiction in a drive is nearing its end of life.

Currently, drive developers monitor stiction by performing contact start stop (CSS) testing on drives. In one method of CSS testing, referred to as mechanical torque measurement (MTM), a torque watch is used to measure a starting torque of the disk spindle. This procedure requires the cover of the drive to be removed in order to measure the disk stack starting torque with the torque watch.

The MTM method of CSS testing has several disadvantages associated with it. In particular, since the drive must be opened to perform the measurement, there is considerable time and human contact involved which greatly increases the risk of damage to the drive. Additionally, opening of the drive exposes the interior to chemical and particulate contamination. Furthermore, in order to perform the CSS testing with the torque watch, the drive must be removed from the test environment. This requirement reduces the relevance of the measurements taken since the data collected is from an environment which is not under test.

Another method of CSS testing involves measurement of the disk spindle starting current required to overcome stiction and initiate disk rotation. In this method, an external device referred to as an electronic

torque meter (ETM) is electrically connected to the hard drive to measure the starting current. This procedure requires the printed circuit board (PCB) of the drive to be removed, and the drive to be removed from its test environment.

Use of an ETM also has a number of disadvantages associated therewith. Since the ETM is an external device which requires the drive to be removed from the test environment, the relevance of the test data is also called into question with this method. Additionally, while the drive does not need to be opened, there is still considerable handling of the drive during removal from the test environment, and also during removal of the PCB. Such handling increases the possibility of damage to the drive. Furthermore, the use of the external ETM to measure stiction relies on detection of back EMF which requires a considerable amount of skill and measurement optimization in order to obtain meaningful results.

Thus, there exists a need for an improved, simple, reliable and cost efficient method for CSS testing of disk drives which does not require excessive handling of the drive and removal of the drive from the test environment.

Summary

The present invention satisfies this need.

The present invention is directed to a method and apparatus for in-drive stiction monitoring of a hard disk drive which includes a spindle motor, a disk stack assembly mounted on the spindle motor, an actuator assembly having a head stack assembly, and controlling circuitry enclosed within an interior of a housing assembly, and a printed circuit board having a motor driver control chip. The method includes steps of initializing registers of the motor driver control chip and initializing the spindle motor, then determining a starting disk position by the circuitry of the motor driver control chip. The motor driver control chip is then used to apply an initial current to the spindle motor and a present disk position is then determined. If the present disk position has changed from the starting disk position, the initial current applied to the spindle motor is identified to be the starting motor current. However, if the present disk position has not changed from the

starting disk position, a next higher current is applied to the spindle motor and the present disk position is again determined. These steps of applying a next higher current to the spindle motor and determining the present disk position are alternately repeated until the present disk position has changed from the starting disk position. When it is determined that the present disk position has changed, the last applied current is identified as the starting motor current. In an additional aspect of the method having features of the present invention, the current applied to the spindle motor is applied as stepwise increments which are a fraction of a maximum spindle current. Preferably, the stepwise increments are less than or equal to about 1/32 of the maximum spindle current. More preferably, the stepwise increments are about 1/256 of the maximum spindle current.

In an alternative embodiment, an improved hard disk drive having features of the present invention includes a spindle motor, a disk stack assembly having at least one rotatable data storage disk mounted on the spindle motor, an actuator assembly having a head stack assembly, and controlling circuitry which are enclosed within an interior of a housing assembly. The housing assembly is defined by a base with integral side walls and a cover. The improved disk drive also includes a removably attached printed circuit board having a motor driver control chip and additional circuitry for controlling disk drive functions, and an in-drive, or on-board, electronic torque meter which includes firmware means for determining contact start stop testing of the drive. The firmware means preferably includes firmware code for initializing the control chip and the spindle motor, determining a starting disk position, applying an initial current to the spindle motor, alternately determining a present disk position and applying a stepwise increasing current to the spindle motor until the present disk position has changed with respect to the starting disk position, and identifying the disk spindle starting current to be a last applied stepwise current prior to change in the present disk position. A further feature of the improved hard disk drive includes firmware code for applying a current step which is a fraction of a maximum spindle current.

The present invention can be used in a variety of diagnostic applications to optimize or improve disk drive development. The present invention provides a non-invasive and unattended manner of obtaining accurate data related to the head disk interface of a hard disk drive. The

present invention also provides a simple and cost efficient way to characterize stiction in an automated and non-destructive manner.

Brief Description of the Drawings

Other features and advantages of the invention will be understood and appreciated by those of ordinary skill in the art upon consideration of the following detailed description, appended claims and accompanying drawings of preferred embodiments, where:

Fig. 1 is an exploded view of a hard disk drive for carrying out a method for in-drive stiction monitoring in accordance with principles of the present invention;

Fig. 2 is a simplified block diagram for carrying out the method in accordance with principles of the present invention;

Fig. 3 is a pictorial illustration graphically showing stepwise application of current to a spindle motor in accordance with an embodiment of the present invention;

Fig. 4 is an example of a listing of firmware code for implementing the method in accordance with principles of the present invention; and

Fig. 5 is graph showing correlation between spindle motor starting currents obtained using an on-board ETM in accordance with principles of the present invention, and an prior art external ETM.

Detailed Description of a Preferred Embodiment

Fig. 1 shows an example of a hard disk drive **10** in which a method embodying aspects of the present invention can be implemented. The disk drive **10** typically is contained in a housing which includes a base **12**, integrally connected sidewalls (not shown), and a cover **14** with a sound damper **16**. The disk drive **10** includes a disk stack assembly **18** having at least one data storage disk **19** rotatably mounted on a spindle motor **20**, and an actuator apparatus or assembly **30**. The spindle motor **20** is typically a

brushless spindle motor integrated into a spindle or hub that supports the data storage disk **19**, such that the spindle motor **20** supports and directly rotates the storage disk **19** at a predetermined angular velocity. The actuator assembly **30** typically includes a magnetic structure **31**, an encapsulated positioning coil **32**, a headstack assembly **34** with attached flex circuit and controlling circuitry **36**, and an actuator lock and filter assembly **38**. The disk drive **10** additionally includes a foam damper **40** and printed circuit board **42** mounted to the housing base **12**. The printed circuit board **42** includes the drive electronics to allow the disk drive to communicate with the computer to which it is connected, and to control operation of the disk drive **10**. Specifically, the disk drive electronics can include a microprocessor, interface electronics, a controller chip or ASIC, a read channel and a motor driver control chip.

Referring to Fig. 2, operation of an embodiment of the in-drive stiction monitoring method according to principles of the present invention will now be described. The method is implemented by first initializing registers of a spindle motor driver control chip **200** on the printed circuit board **42**. The registers are initialized with operating parameters for the spindle motor such as, for example, an initial starting current, current step size and maximum current. Next the spindle motor **20** is initialized **202** prior to a current being applied to affect spindle rotation. A disk rotor starting position is then determined **204** by the motor driver control chip. The disk rotor starting position can be determined using any known rotor position detection algorithm such as a current rise time differential method, or a like position detection algorithm. An example of such a known detection algorithm can be found in U.S. Patent No. 5,028,852 entitled Position Detection For A Brushless DC Motor Without Hall Effect Devices Using A Time Differential Method.

Once the initialization steps **200, 202** are completed and the disk rotor position is determined **204**, an initial current is applied **206** to the spindle motor **20** under the control of the motor driver control chip. The initial current applied to the spindle motor **20** is chosen by the end user and is dependent on the end user's specific needs. After the initial current is applied **206** to the spindle motor, the disk rotor position is again determined **208** to see if the initially applied current was sufficient to affect spindle rotation and change the disk position **210**. If the disk position is unchanged

from the previously determined starting position, a next higher current level is applied **212** to the spindle motor **20**. Alternatively, if the disk position is changed or altered, the last applied current is provided through a head disk interface and reported to the end user as the starting current **214** of the disk drive **10**.

In the event that the disk rotor position remains unchanged after current is applied to the spindle motor **20**, the steps of applying a next higher current level **212** and determining the present disk position **208** are alternately repeated until the disk position has changed. When it is determined that the disk position has changed in response to an applied current, that current is reported as the starting current **214** of the disk drive **10**, as described above.

As described above, a current waveform is applied to the spindle motor **20** as determined by the end user. Within the basic concept of the method there are several adjustments which can be made to this current waveform. As already described, during the initialization steps of the method, the initial current, maximum current and current step size are defined by the user. Additionally, the current ramp, current application and rest timings can be defined by the user. This flexibility in the applied current waveform provides a method that can be tailored to a specific application for which the user requires stiction monitoring. In a preferred embodiment of the method, the current waveform is defined such that the current applied to the spindle motor **20** is in stepwise increments which are a fraction of the maximum motor current. Such a current application is shown pictorially in Fig. 3, where the total current applied at each step is shown in bar graph form. In this embodiment, the stepwise increments are preferably less than or equal to 1/32 of the maximum motor current. More preferably, the stepwise increments are about 1/256 of the maximum motor current. Alternatively, the current application can be defined such that the current level applied to the spindle motor **20** is a predetermined or user defined current level. This embodiment would be useful, for example, in a start/no start determination at a specific current level. Other current applications are also possible.

In another embodiment of the invention, the above described method is implemented as an in-drive, or on-board, electronic torque meter,

which provides an improved hard disk drive. The electronic torque meter includes the motor driver control ASIC on the PCB **42** of the disk drive **10**, and firmware means for carrying out the described method steps. The firmware means is firmware code and can be any known programming language/code, such as, for example, assembler code shown in Fig. 4.

In operation, the above method and apparatus are shown to provide similar test measurements as compared to prior art external electronic torque meters. Fig. 5 shows the correlation between measurements taken with an external ETM and those taken by the on-board ETM of the present invention. In the figure, the measured starting current of the on-board ETM is shown on the y-axis, and the measured starting current of the prior art external ETM is shown on the x-axis. The on-board ETM current is measured in DAC steps where the full scale current is 255 DAC steps, which roughly corresponds to 1500 mAmps. As depicted by the figure, the in-drive ETM of the present invention can provide reliable measurements comparable to those obtained using an external ETM.

As described hereinabove, the stiction monitoring method and apparatus incorporating features of the present invention have a number of useful applications that provide several advantages over the prior art. First, the method and apparatus can be used for measuring spindle motor starting current of a disk drive during CSS testing in an automated, non-invasive manner. Such automated measurements of CSS performance can significantly enhance the ability to gather high quality data related to the head disk interface. In turn, this data can be used to qualify the head disk interface during preproduction of drive development, and as a diagnostic indicator of the head disk interface. Further, the present invention can be integrated into a selfscan CSS test procedure in which the spindle motor is repeatedly spun up and down. Here, the invention can be implemented to measure the spindle starting current as frequently as desired. These more frequent starting measurements can provide greatly improved CSS test data. Additionally, the integration of the on-board electronic torque meter and its operation into the selfscan CSS testing can significantly reduce the amount of time required for CSS testing and the amount of drive handling during CSS testing. Lastly, the non-invasive and automated manner of the present invention significantly reduces human handling of the disk drive, thus allowing testing in any ambient environment and reducing the possibility of

damaging the drive. The present invention therefore provides a more efficient and less error prone CSS test procedure which is shown to produce reliable measurements comparable to prior art external CSS test procedures.

While the present invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The disclosures and description herein are purely illustrative and are not intended to be in any sense limiting.

What is claimed is:

1. A method for in-drive stiction monitoring of a hard disk drive, the disk drive including a spindle motor, a disk stack assembly having at least one rotatable data storage disk mounted on the spindle motor, an actuator assembly having a head stack assembly, and controlling circuitry enclosed within an interior of a housing assembly defined by a base with integral side walls and a cover, and a printed circuit board having a motor driver control chip thereon, the printed circuit board removably attached to the housing assembly, the method comprising steps of:

(a) initializing registers of the motor driver control chip;

(b) initializing the spindle motor;

(c) determining a starting disk position using the motor driver control chip;

(d) applying an initial current to the spindle motor using the motor driver control chip;

(e) determining a present disk position using the motor driver control chip;

(f) applying a next higher current level to the spindle motor if the disk position is unchanged;

(g) indicating a last applied current as the starting current of the disk drive if the disk position is changed,

wherein the stiction monitoring is performed internally to the disk drive without opening the housing assembly or removing the printed circuit board such that damage, due to handling and contamination, to the disk drive is reduced.

2. The method of claim 1 wherein steps (e) - (g) are repeated until it is determined that the disk position has changed from the starting disk position.

3. The method of claim 2 wherein the next higher current level is a stepwise increment which is a fraction of a maximum motor current.

4. The method of claim 3 wherein the stepwise increments are less than or equal to 1/32 of the maximum motor current.

5. The method of claim 4 wherein the stepwise increments are preferably about 1/256 of the maximum motor current.

6. The method of claim 2 wherein the initial current and the next higher current level are user determined values.

7. A method of internally measuring disk spindle starting current of a disk drive device including a spindle motor, a disk stack assembly having at least one rotatable data storage disk mounted on the spindle motor, an actuator assembly having a head stack assembly, and controlling circuitry enclosed within an interior of a housing assembly defined by a base with integral side walls and a cover, and a printed circuit board having a motor driver control chip thereon, the printed circuit board removably attached to the housing assembly, the method comprising steps of:

(a) initializing the control chip and the spindle motor;
(b) determining a starting disk position;
(c) applying an initial current to the spindle motor;
(d) alternately determining a present disk position and applying a stepwise increasing current to the spindle motor until the present disk position has changed with respect to the starting disk position; and
(e) identifying the disk spindle starting current to be a last applied stepwise current prior to change in the present disk position,

wherein the disk spindle starting current is determined in a non-invasive manner to the disk drive such that the housing assembly does not have to be opened and the printed circuit board is not removed.

8. The method of claim 7 wherein the stepwise increasing current is a fraction of a maximum motor current.

9. The method of claim 8 wherein the stepwise increasing current is less than or equal to 1/32 of the maximum motor current.

10. The method of claim 9 wherein the stepwise increasing current is preferably equal to approximately 1/256 of the maximum motor current.

11. The method of claim 7 wherein the initial and stepwise increasing currents are user specified values.

12. An improved hard disk drive system comprising at least a spindle motor, a disk stack assembly having at least one rotatable data storage disk mounted on the spindle motor, an actuator assembly having a head stack assembly, and controlling circuitry enclosed within an interior of a housing assembly defined by a base with integral side walls and a cover, and a printed circuit board having a motor driver control chip and circuitry thereon for controlling disk drive functions, the printed circuit board removably attached to the housing assembly, wherein the improvement comprises:

an in-drive electronic torque meter comprising firmware means for performing contact start stop testing of the drive,

wherein disk spindle starting current is determined in a non-invasive manner to the disk drive such that the housing assembly does not have to be opened and the printed circuit board is not removed.

13. The improved hard disk drive system of claim 12 wherein the firmware means for performing contact start stop testing of the drive comprises:

(a) firmware code for initializing the control chip and the spindle motor;

(b) firmware code for determining a starting disk position;

(c) firmware code for applying an initial current to the spindle motor;

(d) firmware code for alternately determining a present disk position and applying a stepwise increasing current to the spindle motor until the present disk position has changed with respect to the starting disk position; and

(e) firmware code for identifying a disk spindle starting current to be a last applied stepwise current prior to change in the present disk position.

14. The improved hard disk drive system of claim 13 wherein the firmware code for applying a stepwise increasing current to the spindle motor includes firmware code for applying a current step which is a fraction of a maximum motor current.

15. The improved hard disk drive system of claim 14 wherein the current step is less than about 1/32 of the maximum motor current.

16. The improved hard disk drive system of claim 15 wherein the current step is preferably about 1/256 of the maximum motor current.

17. The improved hard disk drive system of claim 13 wherein the firmware code for applying a stepwise increasing current to the spindle motor includes firmware code for applying a current step which is a user specified value.

18. The improved hard disk drive system of claim 13 further comprising:

(f) firmware code for indicating the identified disk spindle starting current to a user.

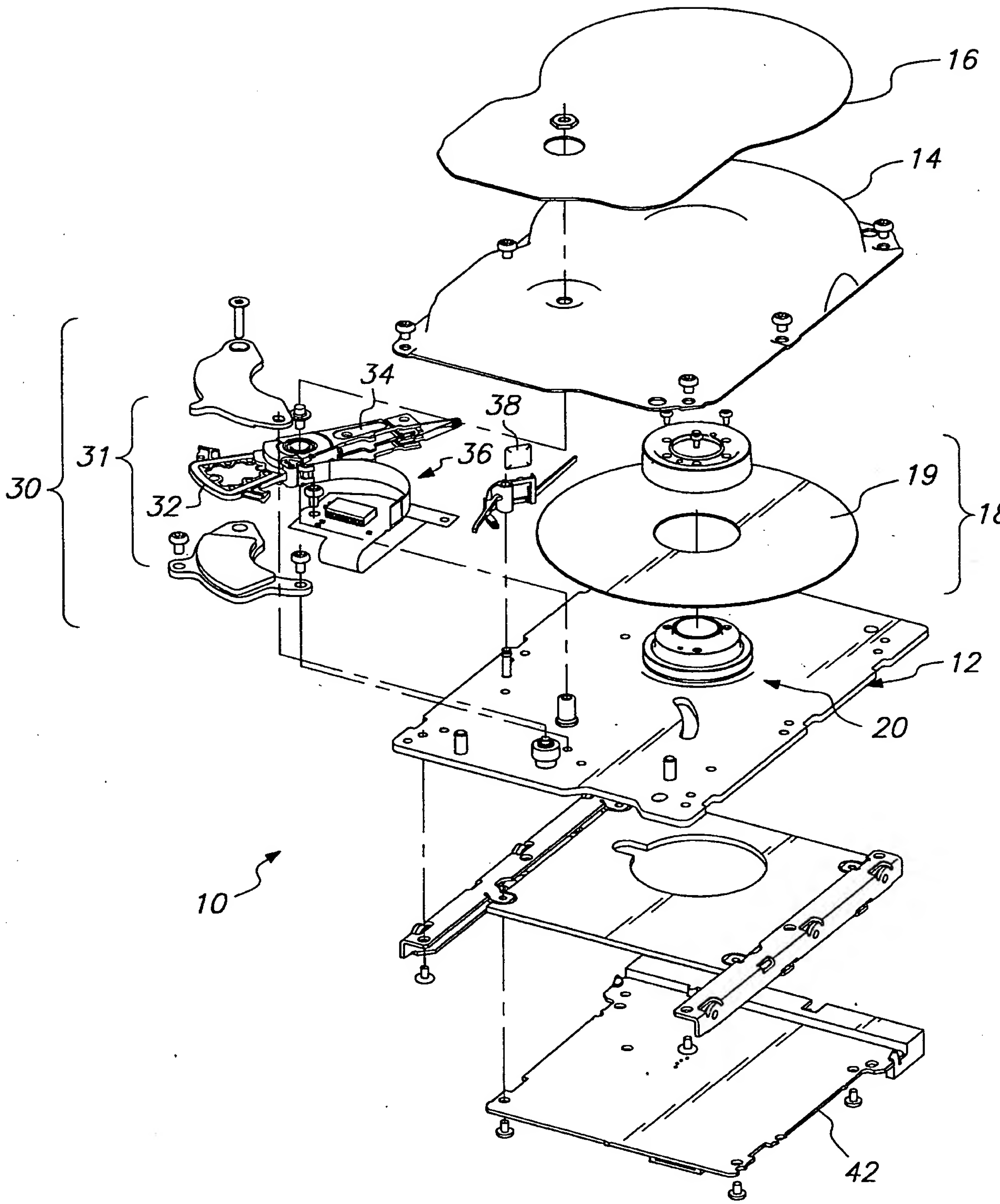

FIG. 1

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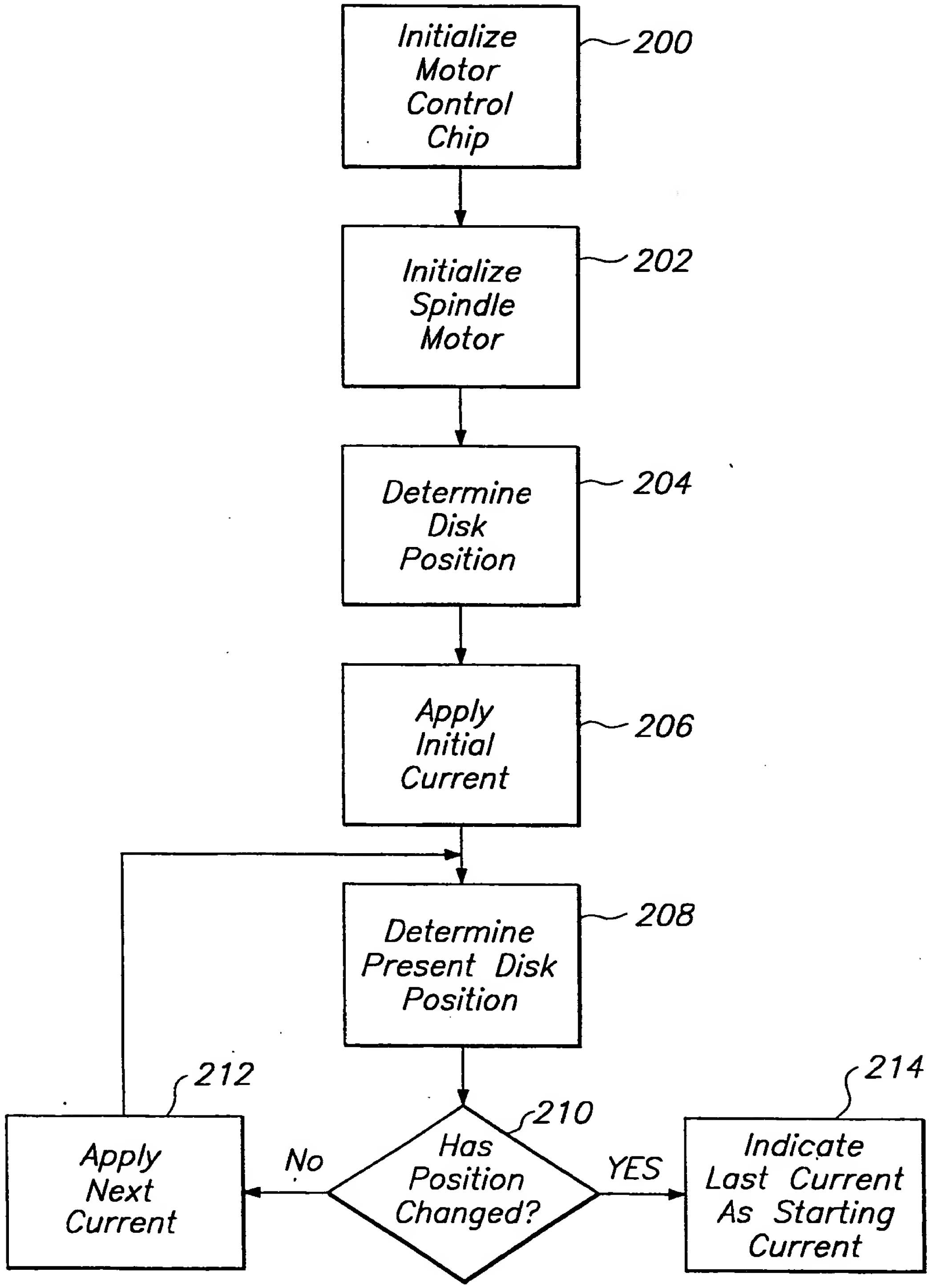
Initialize Motor Control Chip
200
Initialize Spindle Motor
202
Determine Disk Position
204
Apply Initial Current
206
Determine Present Disk Position
208
Has Position Changed?
210
No
YES
Apply Next Current
212
Indicate Last Current As Starting Current
214

FIG. 2

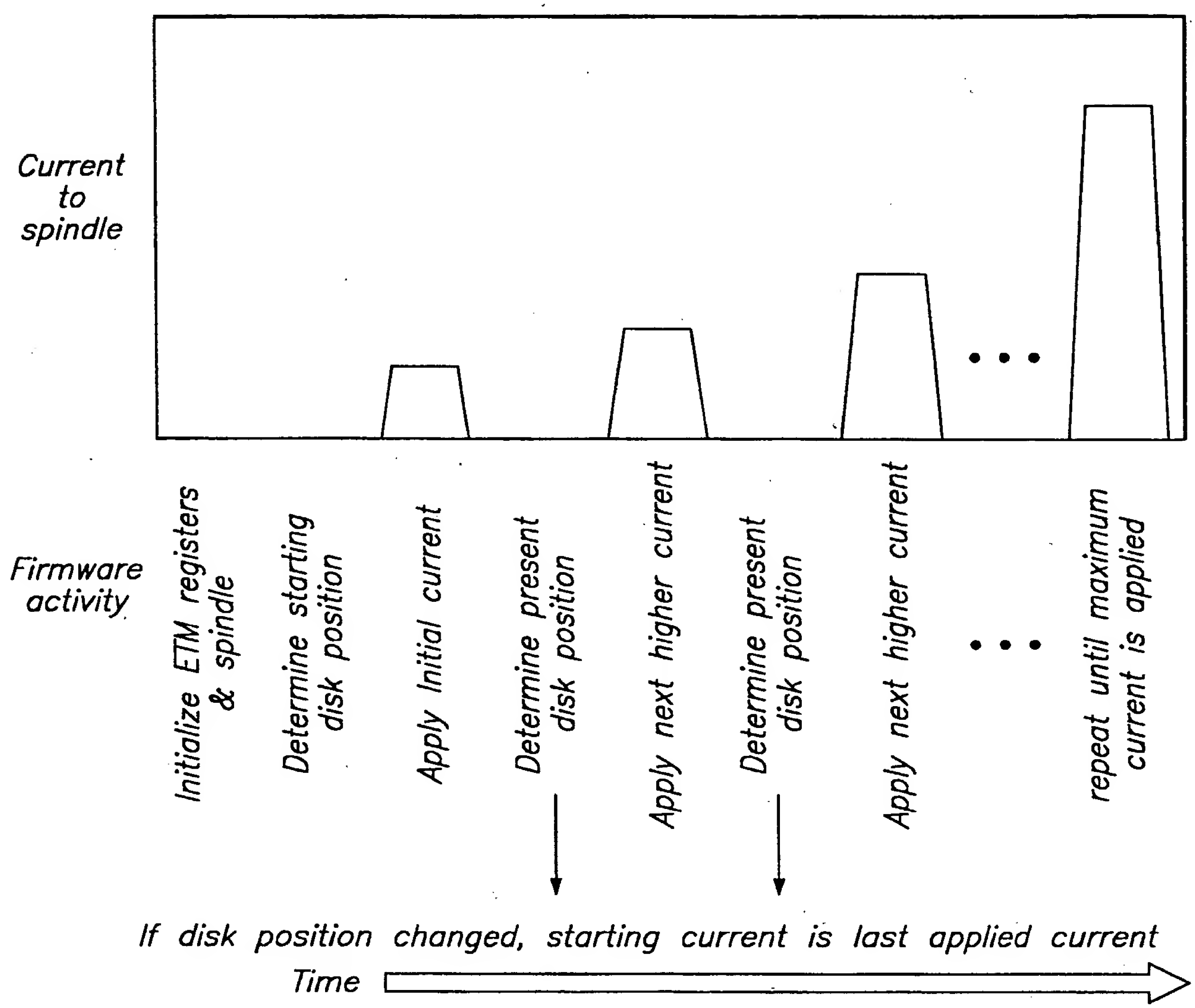
Current to spindle
Firmware activity
Initialize ETM registers & spindle
Determine starting disk position
Apply Initial current
Determine present disk position
Apply next higher current
Determine present disk position
Apply next higher current
repeat until maximum current is applied
If disk position changed, starting current is last applied current
Time

FIG. 3

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```
78K/VII Series Assembler V1.43
Assemble list

 ALNO STNO ADRS   OBJECT    M I SOURCE STATEMENT
;**************************************************************************
****                            ; 1.2
 933 4601                 ;*
; 1.2
 934 4602                 ;*       SUBROUTINE: etm_init          PROGRAMMER:
G. Uhlendorf                            ; 1.2
 935 4603                 ;*
; 1.2
 936 4604                 ;*       DESCRIPTION: set spindle electronic torque meter
default parameters                       ; 1.2
 937 4605                 ;*
; 1.2
 938 4606                 ;*  INPUT ASSUMPTIONS:
; 1.2
 939 4607                 ;*
; 1.2
 940 4608                 ;*  OUTPUT CONDITIONS:
; 1.2
 941 4609                 ;*
; 1.2
 942 4610                 ;* VARIABLES AFFECTED:
; 1.2
 943 4611                 ;*
; 1.2
 944 4612
;**************************************************************************
****                            ; 1.2
 945 4613                          PUBLIC ETM_INIT
; 1.2
 946 4614 00D090                ETM_INIT:
; 1.2
 947 4615 00D090 RB001F5010E          MOV
!!ETM_AL_PWM,#DEF_ETM_AL_PWM; ETM default prealignment current
; 1.2
      00D095 FF
 948 4616 00D096 RB001F6010E          MOV    !!ETM_STEP,#DEF_ETM_STEP
; ETM default resolution                               ; 1.2
      00D09B 02
 949 4617 00D09C RB001F7010E          MOV
!!ETM_START,#DEF_ETM_STEP; ETM default start dac
; 1.2
      00D0A1 02
```

FIG. 4A

```
 950 4618 00D0A2 RB001F8010E        MOV    !!ETM_END,#0FFH       ; ETM
default end dac                                ; 1.2
       00D0A7 FF
 951 4619 00D0A8 RB001FB010E        MOV
!!ETM_REST_HI,#PWM_STL_TIM_HI; ETM default time from rpd to dac ramp
; 1.2
       00D0AD 03
 952 4620 00D0AE RB001F9010F        MOVW   !!ETM_REST,#PWM_STL_TIM
; 1.2
       00D0B3 AA25
 953 4621 00D0B5 RB001FE010E        MOV
!!ETM_RMPR_HI,#DEF_ETM_RMPR_HI; ETM default dac ramp rate delay time
; 1.2
       00D0BA 00
 954 4622 00D0BB RB001FC010F        MOVW
!!ETM_RMPR,#DEF_ETM_RMPR                                               ;
1.2
       00D0C0 A478
 955 4623 00D0C2 RB00101020E        MOV
!!ETM_STL_HI,#DEF_ETM_STL_HI; ETM default time from end of ramp to rpd
; 1.2
       00D0C7 1F
 956 4624 00D0C8 RB001FF010F        MOVW   !!ETM_STL,#DEF_ETM_STL
; 1.2
       00D0CD 8084
 957 4625 00D0CF R2100853F        CALL   !!MTR_OFF              ; spin down
; 3.14
 958 4626                  $      _IF    ATX
; 3.14
 959 4627 00D0D3 RCD2CD145        SET1   DRIVE_READY             ; set for
no spin up on call-subroutine diag                   ; 3.14
 960 4628                  $           ELSE
; 3.14
 961 4629                        CLR1   LOW_PWR_MODE          ; clr for no spin
up on call-subroutine diag                  ; 3.14
 962 4630                        CLR1   PWR_MODE_ENABLED        ; same
; 3.14
 963 4631                        SET1   DRIVE_READY           ; same
; 3.14
 964 4632                  $           ENDIF
; 3.14
 965 4633 00D0D7 03               RET
; 1.2
 966 4634
; 1.2
```

FIG. 4B

SUBSTITUTE SHEET (RULE 26)

6/11

```
 967 4635
;***********************************************************************
****                          ; 1.2
 968 4636              ;*
; 1.2
 969 4637              ;*     SUBROUTINE: etm_align       PROGRAMMER:
G. Uhlendorf                          ; 1.2
 970 4638              ;*
; 1.2
 971 4639              ;*     DESCRIPTION: spindle electronic torque meter
prealignment                          ; 1.2
 972 4640              ;*
; 1.2
 973 4641              ;*  INPUT ASSUMPTIONS:
; 1.2
 974 4642              ;*
; 1.2
 975 4643              ;*  OUTPUT CONDITIONS:
; 1.2
 976 4644              ;*
; 1.2
 977 4645              ;* VARIABLES AFFECTED:
; 1.2
 978 4646              ;*
; 1.2
 979 4647
;***********************************************************************
****                          ; 1.2
 980 4648                     PUBLIC ETM_ALIGN
; 1.2
 981 4649 00D0D8              ETM_ALIGN:
; 1.2
 982 4650 00D0D8 R21005C60          CALL   !!RPD             ; measure initial
position                          ; 1.2
 983 4651 00D0DC R21003262          CALL   !!ADV_ST_PTR        ; advance
one state                            ; 1.2
 984 4652
; 1.2
 985 4653                 ;------DO AN ALIGNMENT TO THE NEXT STATE
; 1.2
 986 4654 00D0E0 RB001F50110        MOV    R0H,!!ETM_AL_PWM      ; get
alignment current                      ; 1.2
 987 4655 00D0E5 B0FF478012        MOV    !!MOTOR_PWM,R0H       ; set
alignment current                      ; 1.2
 988 4656 00D0EA R2100FF61         CALL   !!BEMF_LIN          ; set driver
mode                               ; 1.3
```

FIG. 4C

```
 989 4657 00D0EE R21001A62          CALL   !!COMMUTATE           ;
load/advance state                                       ; 1.2
 990 4658 00D0F2 R21008A61          CALL   !!SPM_FORCE_ST        ; set force
mode                                           ; 1.2
 991 4659
; 1.2
 992 4660 00D0F6 A33E            MOV    R1H,#POS_STL_TIM_HI    ; get
motor pos settle delay time                             ; 1.2
 993 4661 00D0F8 6048F1           MOVW   R0,#POS_STL_TIM       ;
; 1.2
 994 4662 00D0FB R21000463          CALL   !!SET_GP_TIMER        ; start timer
; 1.2
 995 4663 00D0FF RDA02D635FB         BF     GP_TIMER_DONE,$$      ; wait
for timer                                          ; 1.2
 996 4664 00D104 R2100B561          CALL   !!SPM_OFF            ; shut down
motor                                          ; 1.2
 997 4665 00D108 03             RET
; 1.2
 998 4666
; 1.2
 999 4667
;**********************************************************************
****                          ; 1.2
 1000 4668              ;*
; 1.2
 1001 4669              ;*      SUBROUTINE: spm_etm
PROGRAMMER: G. Uhlendorf                                  ; 1.2
 1002 4670              ;*
; 1.2
 1003 4671              ;*      DESCRIPTION: spindle electronic torque meter
; 1.2
 1004 4672              ;*
; 1.2
 1005 4673              ;*   INPUT ASSUMPTIONS:
; 1.2
 1006 4674              ;*
; 1.2
 1007 4675              ;*   OUTPUT CONDITIONS:
; 1.2
 1008 4676              ;*
; 1.2
 1009 4677              ;* VARIABLES AFFECTED:
; 1.2
 1010 4678              ;*
; 1.2
```

FIG. 4D

```
  1011 4679
;***********************************************************************
****                             ; 1.2
  1012 4680                        PUBLIC SPM_ETM
; 1.2
  1013 4681 00D109               SPM_ETM:
; 1.2
  1014 4682
; 1.2
  1015 4683             ;------init vars for ramp to 2 states away from alignment
; 1.2
  1016 4684 00D109 R21005C60        CALL   !!RPD              ; measure initial
position                            ; 1.2
  1017 4685 00D10D RB001EF0170       MOV    R3H,!!PH_STATE_PTR    ; get
initial state                           ; 1.2
  1018 4686 00D112 R21003262        CALL   !!ADV_ST_PTR          ; advance 2
states from present position               ; 1.2
  1019 4687 00D116 R21003262        CALL   !!ADV_ST_PTR          ;
; 1.2
  1020 4688 00D11A RB001EF0160       MOV    R3L,!!PH_STATE_PTR    ; get
target state                             ; 1.2
  1021 4689 00D11F RB001F70110       MOV    R0H,!!ETM_START       ; init
ETM start dac value                        ; 1.2
  1022 4690 00D124 RB001F10112       MOV    !!SPM_ST_TORQ,R0H     ;
; 1.2
  1023 4691
; 1.2
1024 4692 00D129               etm_loop:
; 1.2
  1025 4693 00D129 B0FF47800E       MOV    !!MOTOR_PWM,#0        ; init dac
for ramp                              ; 1.2
           00D12E 00
  1026 4694 00D12F R2100FF61        CALL   !!BEMF_LIN            ; set driver
mode                                 ; 1.3
  1027 4695 00D133 RB001FB0130       MOV    R1H,!!ETM_REST_HI     ; get
time from rpd done to ramp                    ; 1.2
  1028 4696 00D138 RB001F90101       MOVW   R0,!!ETM_REST         ;
; 1.2
  1029 4697 00D13D R21000463        CALL   !!SET_GP_TIMER        ; start
timer                                 ; 1.2
  1030 4698 00D141 RDA02D635FB       BF     GP_TIMER_DONE,$$      ; wait
for timer                               ; 1.2
  1031 4699 00D146 RB001EF0162       MOV    !!PH_STATE_PTR,R3L    ; set
pointer to target state                     ; 1.2
  1032 4700 00D14B R21001A62        CALL   !!COMMUTATE           ; load
state                                 ; 1.2
```

FIG. 4E

SUBSTITUTE SHEET (RULE 26)

```
 1033 4701 00D14F R21008A61            CALL   !!SPM_FORCE_ST        ; set force
mode                                    ; 1.2
 1034 4702
; 1.2
 1035 4703 00D153            dac_ramp_lp:
; 1.2
 1036 4704 00D153 B8FF478030           ADD    !!MOTOR_PWM,#1        ; ramp
dac                                       ; 1.3
      00D158 01
 1037 4705
; 1.2
 1038 4706 00D159 RB001FE0130          MOV    R1H,!!ETM_RMPR_HI     ; get
ramp rate delay time                          ; 1.2
 1039 4707 00D15E RB001FC0101          MOVW   R0,!!ETM_RMPR
; 1.2
 1040 4708 00D163 R21000463            CALL   !!SET_GP_TIMER        ; start timer
; 1.2
 1041 4709 00D167 RDA02D635FB          BF     GP_TIMER_DONE,$$      ; wait
for timer                                 ; 1.2
 1042 4710
; 1.2
 1043 4711 00D16C B0FF478010           MOV    R0H,!!MOTOR_PWM       ; get
DAC value reg                             ; 1.2
 1044 4712 00D171 RB201F1011E          CMP    R0H,!!SPM_ST_TORQ     ; ramp
to target value                           ; 1.2
 1045 4713 00D176 53DB               BL     $dac_ramp_lp
; 1.2
 1046 4714
; 1.2
 1047 4715 00D178 RB001010230          MOV    R1H,!!ETM_STL_HI      ; get
motor pos settle delay time                   ; 1.2
 1048 4716 00D17D RB001FF0101          MOVW   R0,!!ETM_STL          ;
; 1.2
 1049 4717 00D182 R21000463            CALL   !!SET_GP_TIMER        ; start timer
; 1.2
 1050 4718 00D186 RDA02D635FB          BF     GP_TIMER_DONE,$$      ; wait
for timer                                 ; 1.2
 1051 4719
; 1.2
 1052 4720 00D18B R21005C60            CALL   !!RPD                 ; measure present
position                              ; 1.2
 1053 4721 00D18F RB401EF017E          CMP    !!PH_STATE_PTR,R3H    ; see if
at alignment                              ; 1.3
 1054 4722 00D194 5021              BNE    $end_etm         ; end not at alignment
; 1.2
 1055 4723
; 1.2
```

FIG. 4F

```
1056 4724 00D196 RB001F10110        MOV    R0H,!!SPM_ST_TORQ     ; get
last step                                                     ; 1.2
 1057 4725 00D19B RB201F60110        ADD    R0H,!!ETM_STEP       ; calc
next step                                                     ; 1.2
 1058 4726 00D1A0 530F             BC    $etm_error      ; bail if dac rolls over
; 1.2
 1059 4727 00D1A2 RB201F8011E        CMP    R0H,!!ETM_END        ; see if
above max value                                                ; 1.2
 1060 4728 00D1A7 5D08              BH    $etm_error         ; if so, bail
; 1.2
 1061 4729 00D1A9 RB001F10112        MOV    !!SPM_ST_TORQ,R0H     ; save
; 1.2
 1062 4730 00D1AE 0A78FF             BR    $!etm_loop         ; loop
; 1.2
 1063 4731
; 1.2
 1064 4732 00D1B1           etm_error:
; 1.2
 1065 4733 00D1B1 RB001F1010E        MOV    !!SPM_ST_TORQ,#0     ; flag
error                                                       ; 1.2
          00D1B6 00
 1066 4734
; 1.2
 1067 4735 00D1B7           end_etm:
; 1.2
 1068 4736 00D1B7 03             RET                  ; end
; 1.2
 1069 4737
; 1.2
 1070 4738 -------          MASK_CPU      CSEG
; 1.0
 1071 4739                ;------------------------------------------
-------------------------------------------------------; 1.0
 1072 4740                ; Interrupt Service Routines
; 1.0
 1073 4741                ;------------------------------------------
-------------------------------------------------------; 1.0
 1074 4742
; 1.0
```

FIG. 4G

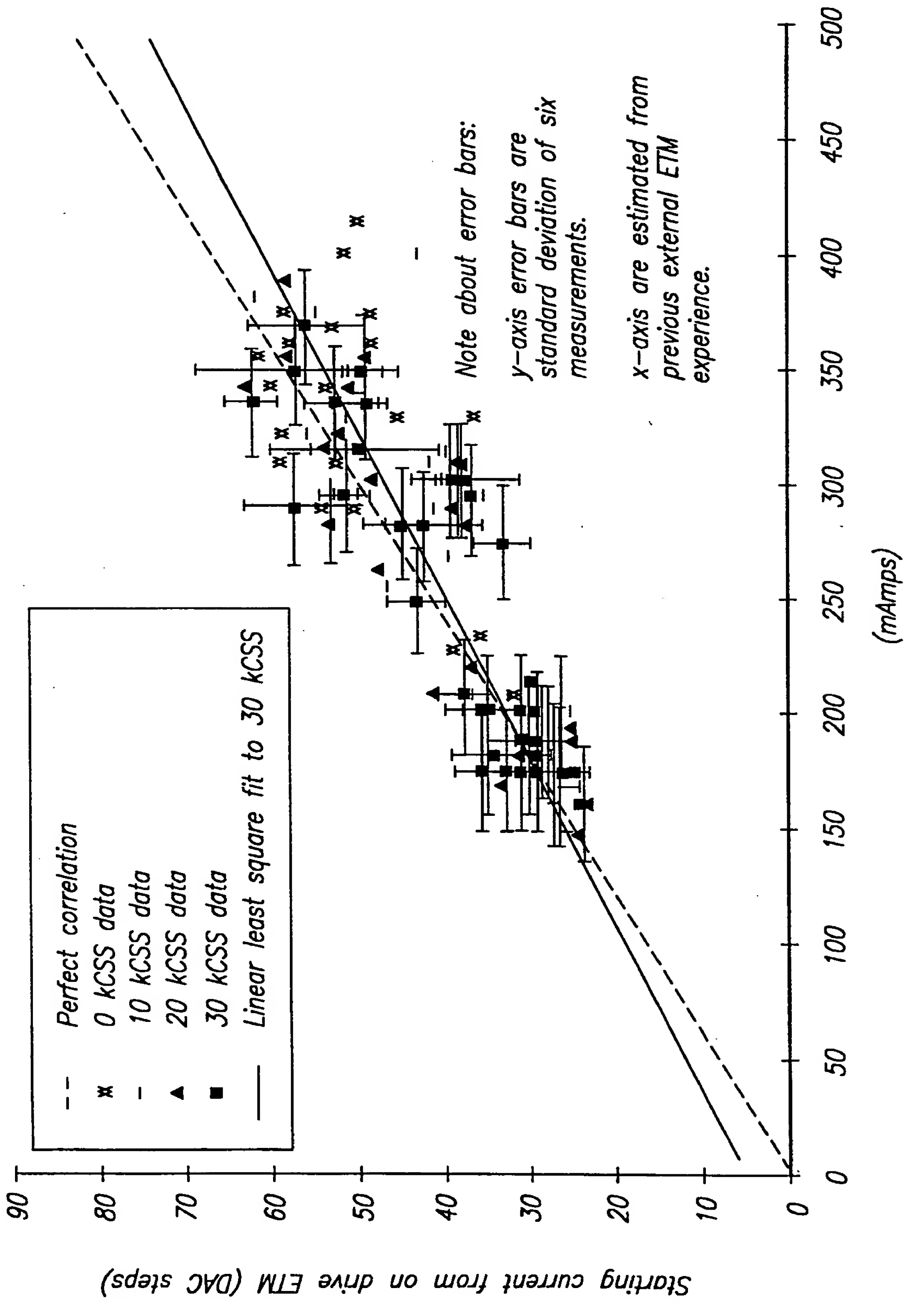
Perfect correlation
0 kCSS data
10 kCSS data
20 kCSS data
30 kCSS data
Linear least square fit to 30 kCSS
Note about error bars:
y–axis error bars are standard deviation of six measurements.
x–axis are estimated from previous external ETM experience.
0
50
100
150
200
250
300
350
400
450
500
(mAmps)
0
10
20
30
40
50
60
70
80
90
Starting current from on drive ETM (DAC steps)

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/02993

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G11B 15/48, 15/46
US CL :360/73.03, 73.01, 69
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 360/73.03, 73.01, 69, 75

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
APS, JPOABS, EPOABS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,557,183 A (BATES et al) 17 September 1996, figs. 1, 2, 3; col. 3, line 58 through col. 4, line 20; col. 4, line 65 through col. 5, line 65; col. 6, lines 60-65.	1-18
Y	US 5,028,852 A (DUNFIELD) 02 July 1991, fig. 6; col. 2, line 20 through col. 3, line 32; col. 8, lines 3-42.	1-18
A	US 4,970,610 A (KNAPPE) 13 November 1990, all.	1-18
A	US 5,018,029 A (EKHOFF et al) 21 May 1991, all.	1-18
A	US 5,235,264 A (KANEDA et al) 10 August 1993, all.	1-18

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
15 APRIL 1998

Date of mailing of the international search report
23 JUL 1998

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/02993

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US RE 34,399 A (GAMI et al) 05 October 1993, all.	1-18